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Time-Frequency Spatial Wavelet Phase Coherence Analysis of EEG in EC and EO During Resting State

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Abstract

The electrophysiological brain activities are nonlinear in nature as measured by Electroencephalography (EEG). There are coherent activities in brain not only seen during explicit tasks but also during rest. This article aims to investigate the Wavelet based Phase coherence of oscillations of eye closed and eye open signals during resting states. The wavelet coherence is computed for selected 19 electrodes according to 10-20 system from 129 channel EEG signals. The significance was obtained using Wilcoxon Signed Rank test and pairwise wavelet coherence was computed for each possible combination. The Wavelet Phase Coherence using Wavelet Transform gives significantly high results (P<0.05) in EC and EO signals during resting states in frequency interval 0.5-50 Hz overall as well as in the band intervals such as delta (05-4 Hz), theta (4-7 Hz), alpha (7-13 Hz), beta (13-22 Hz) and gamma (22-50 Hz).

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1. Introduction

The nonlinear dynamics in normal resting state EEG are primarily concerned to study the dynamics in normal EEG particularly in alpha rhythm. The previous studies [1] reveal that normal EEG are reflecting weak but

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significantly nonlinear structure (Gautama et al., 2003; Gebber et al., 1999; Maurice et al.,2002; Meyer-Lindenberg, 1996; Palus, 1996c; Pritchardet al., 1995a; Rombouts et al., 1995; Stam et al., 1999; Stepien, 2002). Previous studies also reveal that alpha activity in EEG is dominant in normal individuals during eye-closed resting condition and suppresses as visual stimulation. Alpha activity decreased during occipital regions (Berger, 1933; Adrian and Matthews, 1934; Jasper, 1936; Smith, 1938) and also in posterior regions when the individuals open their eyes (Chapman et al., 1962; Volavka et al., 1967; Legewie et al., 1969; Glass and Kwiatkowski, 1970; Gale et al., 1971). These studies suggest that alpha desynchronization reflects the increased visual system functioning due to visual stimulation being mediated by the Reticular Activating System (Volavka et al., 1967; Gale et al., 1971; Hardle et al., 1984). (Deco et al., 2008, 2009; Ghosh et al., 2008 also found a surprising degree of complexity and coherent activities in human brain during resting states EEG.

In this paper we aimed to investigate the nonlinear dynamics in EEG signals in healthy subjects with eye open and close using Wavelet Phase coherence during resting state. Coherence measure is the phase difference between two signals weighted by amplitude and measured over time in particular frequency. The values of coherence range from 0 to 1, if the value of coherence is 1, it shows the complete agreement in phase difference, and 0 shows the completely random phase difference. This study is aimed to study the EEG coherence by computing topographic and frequency structure. For topographic information, the coherence will be computed over different location such as inter-hemispheric and intra-hemispheric locations, local and global, sagittal and literal etc. in different frequency ranges and relationships in different coherence pairs.

2. Material and Methods

2.1. Data Sets

EEG data with eye–closed (EC) and eye open (EO) during resting states comprising of 129 channels was taken from Neurophysiological Biomarker Toolbox accessible from URL:
(https://www.nbtwiki.net/doku.php?id=tutorial:start#.VVXEKkaLXEs) as used and discussed in [2]. The Data contains 16 healthy volunteers (ten females, median age: 27 years, range 21–48) with no history of neurological or psychiatric illness, illegal substance abuse or use of psychotropic medication".

2.2. Methods

In time-frequency plane, we can know the frequency of an oscillation at every point in time that is influenced by time dependent component. Thus in phase space, the complexity and frequency domain may fail to interpret the useful information of non-autonomous system [3]. The wavelet transform is of time series is then obtained by convolving the complex wavelet of equation 1) with the time series at each scale s. i.e.

$$W(s,t) = \int_{-\infty}^{\infty} \Psi\left(\mathrm{s},(\mathrm{t},\tau)\right) f(\tau) d\tau \qquad (1)$$

The Morlet wavelet transform as defined in 1) was applied to EC and EO in resting states for 19 electrodes according to 10-20 international system. We have used the central frequency of $\omega_o = 2$ and rescaling in increments of 5 % between s=0.5 and 80 Hz.

When there are two noisy signals interacting to each other with different spectra in power at same frequency, their oscillation whether related or unrelated can be detected significantly over time using the phase coherence.

Thus time-averaged wavelet phase coherence as defined in [4].

$$\pi_p = \frac{1}{L} \sqrt{\left(\left\{ \sum_{n=1}^{L} \sin[\varphi(t_n)] \right\}^2 + \left\{ \sum_{n=1}^{L} \cos[\varphi(t_n)] \right\}^2 \right)} \quad (2)$$

The wavelet values of equations (4) can be replaced with a normalized phasor as defined by [4].
The averaged phase coherence is defined as:

$$\pi_p = \left[\left(\frac{1}{L_k}\sum_{n=1}^{L} e^{i\varphi_1(t_n)}\ e^{-i\varphi_2(t_n)}\ \right)\times\left(\frac{1}{L_k}\sum_{n=1}^{L} e^{-i\varphi_1(t_n)}\ e^{i\varphi_2(t_n)}\ \right)\right]^{1/2} \quad (3)$$

We can find $E(\pi_p)$ to calculate autocorrelation and G_k statistics using $W_k(t_n)$ of the unit phasor for the new time series.

3. Discussions

The coherence was computed for 19 electrodes as mentioned above for all possible combinations and resultant matrices contains enormous information which required to be shown in form of topographic maps in one plot. We have computed coherence for each frequency band such as delta, theta, alpha, beta and gamma for both eye-closed and open during resting states. Each large circle in these figures shows the whole scalp where a small topographic map is placed at each electrode position also repessing a scalp and contains the coherence with all possible combination of electrodes.

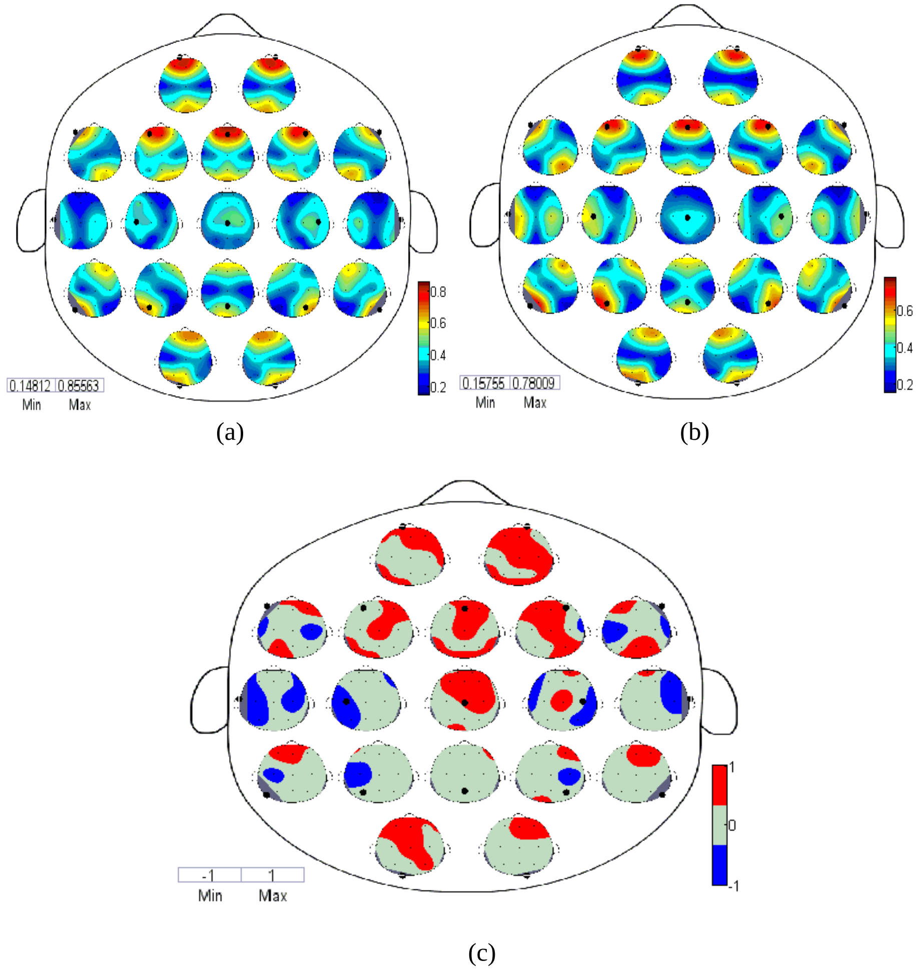

Fig. 1: (a) Wavelet coherence EC, (b) EO (c) Significance using paired test for each 19 electrodes in topographic maps. This figure contains 19 small topographic maps according to 10/20 international system inside a single head display. The map provide full picture of 129 electrodes of EC subject during resting state in delta frequency band (red: EC>EO; blue: EC<EO; grey: No significance)

4. Discussions and Conclusion

The aim of present study is to investigate the temporal dynamics of resting state EEG using coherence and topographic maps. We have computed wavelet coherence and examined in detail the topography and frequency structure of EEG coherence during resting state in EC and EO subjects. The topographic changes have been observed in delta, theta, alpha, beta and gamma bands however most significant differences were seen in alpha band as reflected in Figure 1 and detailed results for other bands are shown in Table 1.

Table 1: Pairwise Wavelet Coherence with statistical significance ($p<0.05$) using Ranksum test

Prob	**Delta**	**Theta**	**Alpha**	**Beta**	**Gamma**
C3	None	O1	F8,Fp1*,P3,T7,P7	None	O1
C4	None	Cz*	Cz*,F7,P4, T7	None	None
Cz	F7	C4*,F4*	C4*,F3*,F4*,Fp1*,Fp2*,Fz*,O1*	F4*	T7,T8,P8
F3	T8*	None	Cz*,F4*,F8*,Fp2*,Fz*,O1*,P7*	None	None
F4	None	Cz*	Cz*,F3*,F7*,Fp1*,O2*,P4*,P8*	Cz*	None
F7	Cz	None	C4,F4*,F8*,Fp1*,Fp2*,Fz*,O1*,P3*	None	None
F8	None	None	C3,F3*,F7*,Fp1*,P4*,Pz*,P8*	None	None
Fp1	Fp2*,T8*	Fp2*,T8*	C3*,Cz*,F4*,F7*,F8*,Fp2*,T8*,P7*	Fp2*	Fp2*
Fp2	Fp1*,Fz*,P3*, T7*,P7*	Fp1*	Cz*, F3*,F7*,Fp1*,Fz*,O2*,P7*,P8*	Fp1*,Fz*	Fp1*,Fz*,O1*
Fz	Fp2*	None	Cz*,F7*,Fp1*,Fp2*,O1*,O2*	Fp2*	Fp2*
O1	None	C3	Cz*,F3*,F7*,Fp1*,Fz*	None	C3,Fp2*
O2	None	None	F4*,F7*,F8*,Fp2*,Fz*	None	T8
P3	Fp2*	None	C3,F7*	None	None
P4	None	None	C4,F4*,F8*	None	None
Pz	T8	None	F8*	None	None
T7	Fp2*,P8	None	C3,C4,P7	None	Cz,P8
T8	F3*,Fp1*,Pz	Fp1*	Fp1*	Fp2	Cz,O2
P7	Fp2*	None	C3,F3*,Fp1*,Fp2*,T7	None	None
P8	None	None	F4*,F8*,Fp2*	None	Cz, T7

Generally, coherence in EC subjects increases in some bands and decreases in other. Pairwise coherence was computed excluding self-coherence in the form of topographic maps. The highest coherence was observed in EC in frontal regions in alpha band. Whereas other bands such as delta, theta, beta also exhibit high coherence in frontal regions in both EC and EO subjects and gamma shows high coherence in EC in Fz and Fp2 only. The parietal regions also shows high coherence in Alpha and Beta bands for both EC and EO and few parietal regions also shows coherent activity in delta and gamma bands. Most of the immediate adjacent electrodes show the higher coherence at all frequency bands [5]. It was also observed overall that when the spatial distance between the electrodes increases the coherence also decreases for both EC and EO at all frequency bands (In Table 1, the * denote that where coherence of EC was higher than EO).

During EC, the highest pairwise coherence in alpha band was observed in frontal regions (F3-Fp1, F4-Fz, Fp1-Fz, Fp2-Fz, Fz-Fp2), the other bands also shows high coherent activities in frontal (F3-fp1, F4-Fz,Fp1-F3, Fp2-F4), occipital-parietal (O2-P8), parietal (P3-P7, P4-P8, P7-P3, P8-P4) and parieto-occipital (P7-O1) regions. A high posterior (P3-P7, P7-P3) coherence is also shown in alpha band with EO.

In human, the oscillations with electric potential 8-12 Hz range with greater amplitude in posterior regions usually recorded as sinusoidal waves and present 95% in healthy adults usually during eye-closed resting state [6]. In the neocortex this potential is believed to arise from the oscillation of postsynaptic potentials (Berger, 1929; Cooper et al., 1965; Nunez et al., 2001). The alpha rhythm is considered as idle and diminish when the eyes are open or during mental activity. In alpha band, there is an apparent reduction in activity from eye closed to eye open condition with no topographic change. The global alpha reduction activity is consistent with the previous EEG studies reporting that across the scalp alpha desynchronization take place due to onset of visual stimulation Adrian and Matthews, 1934; Jasper,1936; Smith, 1938; Chapman et al., 1962; Volavka et al.,1967; Legewie et al., 1969; Glass and Kwiatkowski, 1970;Gale et al., 1971). Previous studies only revealed that entire cortex is activated in response to visual stimulation due to desynchronization in alpha activities (Basar and Schurmannn, 1999) and have not distinguished the arousal and activation activities in this way.

Delta activity [7] during early development dominates the human EEG and decreases during normal development (John et al., 1980; Gasser et al., 1988; Harmony et al., 1990). Slow wave delta activity in development is deemed important to support brain maturation and prune redundant cortical connections to exhibit positive association between gray matter volume and delta activity (Whitford et al., 2007). Whereas the high wave delta activity recorded during reading tasks is observed in dyslexic school age children (Spironelli et al., 2006; Penolazzi et al., 2008; Spironelli and Angrilli, 2010) and dyslexic young adults (Rippon, 2000). However, increased delta and theta activity is reported in children with reading and writing disabilities and in dyslexics in resting state EEG at the age 9-18 years (Sklar et al., 1972; Colon et al., 1979; Pinkerton et al., 1989; Harmony et al., 1995).

The pathological and ordinary human brain functions investigated by [8] measuring the corticocortical connectivity. (Thatcher et al., 1986; Tucker et al., 1986) estimated the coherence in frequency spectrum of EEG studies in resting state subjects and measured the coupling functions across distinct brain regions of human brain. (Scher et al., 1994) studied the coherence of various intrahemispheric and interhemispheric regions and found greater EEG spectra patterns in preterm infants than in full-term infants which indicate the increased neuronal connectivity due to extrauterine experience. (Lowe et al., 1998) investigated the coherence in left and right hemisphere in resting states single and multi-slice echoplanner data in right and left hemisphere, precentral gyri (motor cortex), calcarine fissures (visual cortex), and right and left hemisphere amygdalae. They observed low frequency correlations in resting state data found in left/right symmetric functional cortices and assessed for whole brain functional connectivity as well.

Several recent studies (Von 1999; Cisek and Turgeon 1999; Varela et al. 2001; Singer 1993; Womelsdorf and Fries 2007) show that brain contains disparate and multiple neural activities in underlying cognition such distributed information requires a mechanism of multiregional function interaction.

(Besthorn et al. ,1994; Locatelli et al., 1998; Babiloni et al. ,2004; Jelles et al.,2008; Sankari and Adeli 2011) investigated EEG coherence in 16, 17 and 19 electrodes according to 10-20 international system. They estimated coherence for individual electrode and all neighboring pair electrodes, fronto-parietal, interhemispheric and intrahemispheric networks, distal and anterior-posterior regions. A decrease in average coherence was seen in frontal and central regions of theta, alpha and beta bands in AD patients. Moreover, particular coherence was identified in AD patients with controls. [5] evaluated the functionality of cortical connectivity and synchronization of regional cortical connectivity in AD patients using EEG coherence measure. The cortical connectivity in AD declined due to decrease in coherence and have potential to distinguish the AD and control subjects.

Relative power and coherence used by [9] to analyze the amnestic mild cognitive impairment in diabetes. They investigated alpha coherence and correlations in intra region (parietal) and inter region (right temporo-posterior, fronto-posterior), interhemispheric (LH, RH), Left posterior (LP)-right posterior (RP) regions in aMIC and control groups and found significant results in alpha frequency band while other bands exhibits no significant differences. From the results, it is evident that topographic maps show differences in arousal and activation during EC and EO. Thus these are not considered as baseline conditions. Moreover, topographic maps using wavelet coherent methods high distinguish the conditions using phase synchronization properties computed from wavelet transform. Thus wavelet coherence methods are more robust to analyze the nonlinear dynamical problems. Thus pairwise Wavelet Coherence in all frequency bands was computed and summarized to see the overall affect EEG in EC and EO during resting state. The table and topographic maps also depicts the increase and decrease of coherence in inter-hemispheric and intera-hemispheric regions. Thus the current researches will insight the future researches as a biomarker for complex and nonlinear physiological markers in EEG with different pathologies.

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